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A Combination Suspended-Load Sampler and Velocity Meter for Small Streams

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INTRODUCTION

This circular is a report on an instrument [1] that will simultaneously collect suspended-load samples from, and measure the velocity of, small streams, an instrument that is especially useful in certain phases of present investigational work of the United States Department of Agriculture pertaining to the effects of soil, slope, vegetal cover, and land use on the occurrence and control of floods, erosion, and sedimentation in reservoirs, stream channels, and on valley agricultural lands. The instrument offers elements of economy and comparative ease and speed of operation without sacrificing accuracy, when used on small streams draining a few hundred or an occasional several thousand square miles. The prime advantage is its applicability where no rated stream-flow stations now exist.

[1] The entire personnel of the Soil Conservation Service sediment-load laboratory aided, by suggestions and assistance, in the development and testing of the device. It was designed in collaboration with H. A. Einstein, who made numerous suggestions, especially as to the manner of making the tests. The many samples collected during the tests were analyzed under the direction of R. G. Grassy at the sedimentation laboratory, Greenville, S. C.; Joe W. Johnson aided by constructive criticism and discussion; and A. T. Talley assisted in the construction of the circulating flume and various other appurtenances used in the experiments. The sediment-load laboratory is under the direction of G. C. Dobson, Chief of the Sedimentation Division of the Soil Conservation Service.

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The Character and Quantity of Suspended-load Sediment

The sediment load of a stream consists of two parts, the bed load and the suspended load. Bed load has been defined as the coarser material that moves close to the bed by sliding, rolling, or saltation, whereas the suspended load is the relatively fine material that moves with the water in suspension and strikes the bed only at comparatively long intervals. Obviously there is no sharp line of demarcation between bed load and suspended load as one grades into the other.

Estimates of the quantity, as well as the type of sediment transported by a river, are necessary basic data for the design and operation of many engineering works. Many quantitative estimates and their application to particular problems have been described in engineering literature (*3*, *4*, *5*, *7*, *10*, *12*, *13*, *14*).[2] These estimates are almost always based either on measurements of accumulation of sediment in settling basins such as storage reservoirs, or on samples of the suspended load of streams.

A few attempts have been made to estimate the quantity of sediment transported by a stream as bed load by applying rational formulas (*12*) and by using portable traps (*13*), but these have met with only partial success. On the other hand, the suspended load of sediment has been determined with considerable accuracy where discharge is measured by frequent sampling of the stream flow at a sufficient number of points in a cross section. From such samples the character of the solid material as well as its volume can be ascertained.

Even though the suspended load can be measured, it cannot, in contrast with bed load, be related to any definite or readily observed hydraulic factor of the stream, such as discharge. This lack of relationship is due primarily to the fact that the supply of the very fine material, which constitutes the predominate portion of the suspended load, depends on such complexly interrelated, and in part changing, factors as topography, soils, shape and size of the drainage basin, land use, vegetal cover, surface and underground storage, and climatic conditions. Or, in other words, the available bed load in a stream system ordinarily changes slowly over a long period of years and the quantity of bed load moved is mainly a response to discharge, while the suspended load may vary greatly from year to year and from season to season because of changing conditions of supply which are independent of conditions of flow.

In many small flashy streams almost all of the annual suspended load is carried during a few days out of a year and the content of suspended sediment may vary many hundred percent within a period of an hour during the rising or falling stage of the stream. There appears to be no means of estimating or computing with even approximate reliability the suspended load carried by any such small stream except by careful frequent sampling during floods (*10*).

Sediment carried by a stream in suspension is usually more concentrated near the bed than near the surface. This is particularly true of the larger and heavier particles. The smaller particles, however, are more uniformly distributed throughout the depth. A

[2] Italic numbers in parentheses refer to Literature Cited, p. 25.

typical load distribution ranging from the surface to the bed of a stream is illustrated in figure 1. Such a distribution usually is referred to simply as a vertical.

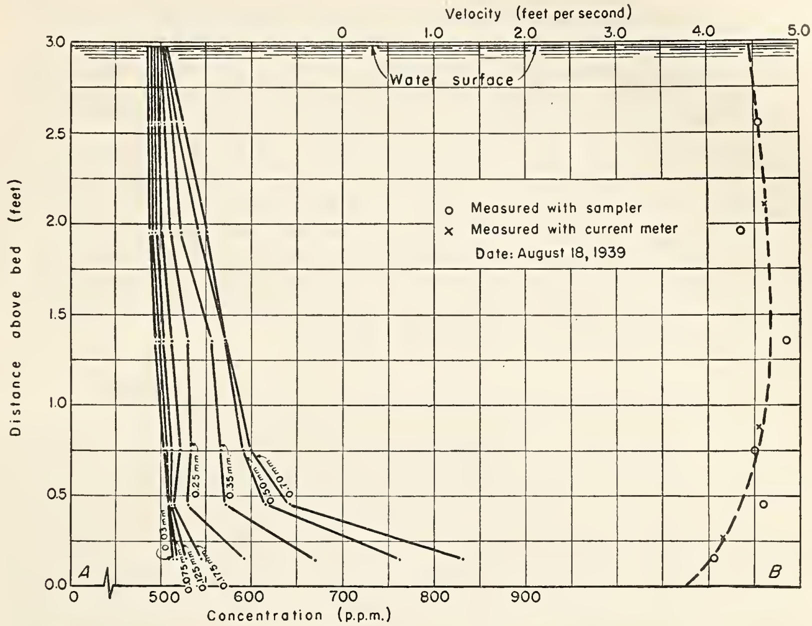

FIGURE 1.—Suspended-load (A) and velocity (B) measurements in Enoree River, S. C.

STANDARDS OF ACCURACY AND METHODS OF DETERMINING QUANTITY

In order to obtain the most accurate determinations of the suspended load and the average composition of the material, a stream should be sampled at a great many vertical and horizontal points in a cross section, the samples at each point to be taken during an interval long enough to eliminate the instantaneous variations often reflected in "clouds" or "boiling" observable in heavily sediment-laden streams. For precise work, velocity measurements should also be made at the sampling points at frequent intervals to permit the rate of suspended-load discharge to be calculated. It is possible, however, where lower degrees of accuracy will serve the immediate practical purpose, to simplify the procedure to the collection of only a few, or even one sample, with similar reductions in the number of velocity measurements, or their omission at previously rated stations equipped with staff gage or stage recorders.

The purpose of the sampling and the accuracy required determine the type of sampler and methods to be used. In certain cases investigators have considered it sufficiently accurate merely to dip a sample out of the stream at almost any point. In most work, however, greater accuracy was desired and samples have been taken by integration throughout the entire depth. Integration, in this sense,

was achieved by the practice of lowering a closed air-filled sampler to the bed of the stream, removing the stopper, and then raising the sampler at a speed such that it would be filled upon reaching the surface. To obtain an average sediment concentration over the complete cross section, the integration process was repeated in several verticals across the stream.

Other methods provide for sampling at fixed points in the stream to obtain a mean comparable to that provided by true integration. In studies of load distribution in the Missouri River (*12*), it was concluded that in a given vertical the flow could be sampled at 0.2 and 0.8 of the depth below the water surface and the average load throughout the vertical obtained by taking five-eighths of the load at the 0.2 depth plus three-eighths of the load at the 0.8 depth. In a study of the silt load of Texas streams, Faris (*3*) concluded that the mean silt concentration in a cross section could be determined by taking samples at the 0.6 depth in verticals at one-sixth, one-half, and five-sixths of the distance across the stream.

The Suspended-Load Sampler and Velocity Meter

As the discharge of a stream may be computed from velocity observations at 0.2 and 0.8 depth, as well as at 0.6 depth, in several verticals, a device that will measure simultaneously the average suspended-load concentration and the flow velocity at a particular point in a stream obviously is of advantage, particularly when used at locations on a stream where no rating curve has been developed, or when time required for observations is an important factor. Recent research studies (*1*) made by the Sedimentation Division of the Soil Conservation Service on the transportation of sediment in natural streams has resulted in the development of such an apparatus. Furthermore, multiple arrangement of these samplers on a vertical rod permits the measurement in a single operation of sediment concentration and velocity throughout the depth of the stream.

The instrument was developed for use in research studies on small streams, but it is also adaptable to more general use. It is particularly well suited for work on small streams where a discharge rating curve is not available, for by using the instrument as a velocity meter, such a rating curve can be constructed. In more accurate work, the instrument is limited to use in submergence depths of 6 feet or less and in streams with flow velocities of 6 feet per second or less. The maximum stream depth, of course, may be greater than a limiting submergence depth of 6 feet, depending upon the method of sampling. For instance, if the 0.6-depth method is used, the maximum stream depth may be 10 feet; if the 0.2- and 0.8-depth method is used the maximum depth may be 7.5 feet.

An accurate average concentration of suspended load is obtained at a point provided the greater percentage of the material has a particle size less than 0.10 mm. in diameter (fig. 1).

In this circular is discussed the development, construction, calibration, use, and hydraulics of the combination suspended-load sampler and velocity meter.

EARLIER SAMPLERS

A number of samplers have been developed by investigators in the past for varying conditions of use. Samples may be collected with a sampling device designed for either instantaneous or gradual filling. Practically instantaneous filling furnishes a single value for the momentary concentration of suspended matter at a sampling point. Gradual filling, on the other hand, gives a certain average value.

The most widely known samplers of the first type are those used by Fortier and Blaney (*5*) and Eakin (*2*); of the second type, the samplers used by Faris (*3*), United States Geological Survey (*9*), Kansas City District, Corps of Engineers, United States Army (*12*), Frazier (*6*), and the United States Bureau of Reclamation (*9*). As none of these samplers was designed for measuring both the flow velocity and the suspended-load concentration, it is necessary either to use them at a gaging station or to determine the velocity with a current meter. It is impossible, however, to use the current meter and sampler at the same point at the same time. Furthermore, when used at different times it is difficult to be certain that the current meter and sampler will be located at identical points, and hence that the measurements will be strictly comparable.

To the author's knowledge, the only instrument developed to permit simultaneous measurement of average sediment concentration and average velocity at a certain point in a stream, other than the one discussed in this circular, is the Gluschkoff sampler used in Russia, described by Jakuschoff (*8*). This sampler consists of a very thin rubber bladder having a capacity of approximately 900 cc. when filled. The bladder intake is connected to a 6-mm.-diameter tube, which is fastened crosswise to a long handle. The handle is lowered into the water in such a manner that the tube opening is pointing downstream. When the desired depth is reached, the handle is turned so that the tube faces and is parallel to the flow. The bladder starts filling immediately as a result of dynamic pressure. To stop the filling process, the handle is turned so that the entrance tube is again pointing downstream.

THE COMBINATION SUSPENDED-LOAD SAMPLER AND VELOCITY METER

Description of Sampler and Support

The combination suspended-load sampler and velocity meter, which utilizes the principle of the Gluschkoff sampler, consists essentially of two tubes fitted through a rubber stopper and inserted into an ordinary pint milk bottle. Details of the instrument, which is unusually simple in construction and comparatively easy to use, are shown in figure 2. Water and sediment enter through the lower tube and the air in the bottle is forced out through the upper tube, which is bent backward over the bottle in the direction of the stream flow.

Both tubes are bent slightly upward inside of the bottle to increase the volume of sediment-laden water that may be trapped and to reduce to a minimum the constant static head that exists between the inside end of the water tube and the outside end of the air tube

A small static head is desirable to overcome the effect of water drops that may collect in the air tube when the sampler is being lowered in streams of low velocity and to counteract to some extent entrance losses. The tube, through which the water enters, projects forward from the stopper a sufficient distance to minimize the effect of the container upon the flow near the entrance of the tube, but not so far as to appreciably alter the compactness of the sampler.

Various methods of supporting the sampler may be used, depending upon particular field conditions. Samples from shallow streams can be taken by wading. Figure 3 (*A*, *B*, and *C*) shows a multiple arrangement of samplers suitable for use when wading. Figure 4 shows the details of a simple holder.

The position of each sampler in a vertical is determined by its position on the support, the base of which rests on the stream bed. The number of samples that can be taken in a vertical is limited only by the size of the bottles used and the depth of the stream. A sample can be obtained approximately 0.15 foot from the bed with

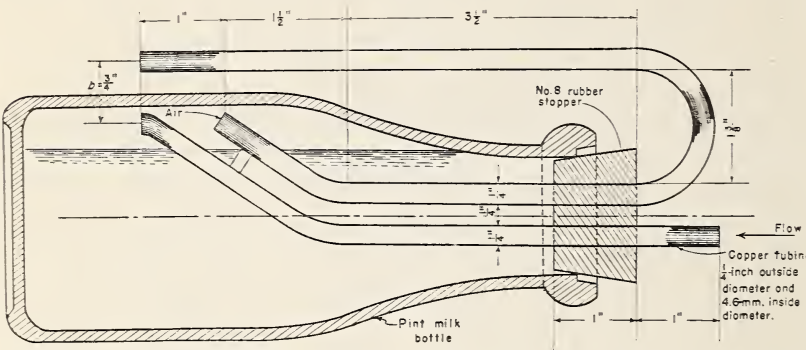

FIGURE 2.—Detail of construction of combination suspended-load sampler and velocity meter.

a satisfactory minimum spacing of successive samplers of approximately 0.30 foot.

For use in deeper streams, where it is necessary to make observations from a cable car or bridge, a suspended sampler support, weighted by two current-meter weights of sufficient size to hold the support vertical, has proved practical. The weights are mounted on either side of the support on a horizontal bar approximately one foot from the base, permitting samples to be collected near the bed and away from any interference to flow due to the weights. Fifteen-pound current-meter weights have been found to give satisfactory results in a stream 5 feet deep, having a velocity of 3 feet per second.

Figure 3 (*D*) shows a multiple arrangement of samplers suspended from a cable car used in gaging streams. An ordinary United States Geological Survey type current-meter reel with one-eighth-inch cable has been used to raise and lower the apparatus and to measure the depth of flow. The cable can be calibrated to tenths of an inch by tags or painted stripes. Figure 5 shows the details of the cable-suspension support with provisions made for clamping samplers at 0.3-foot intervals. Any other desired interval can be used.

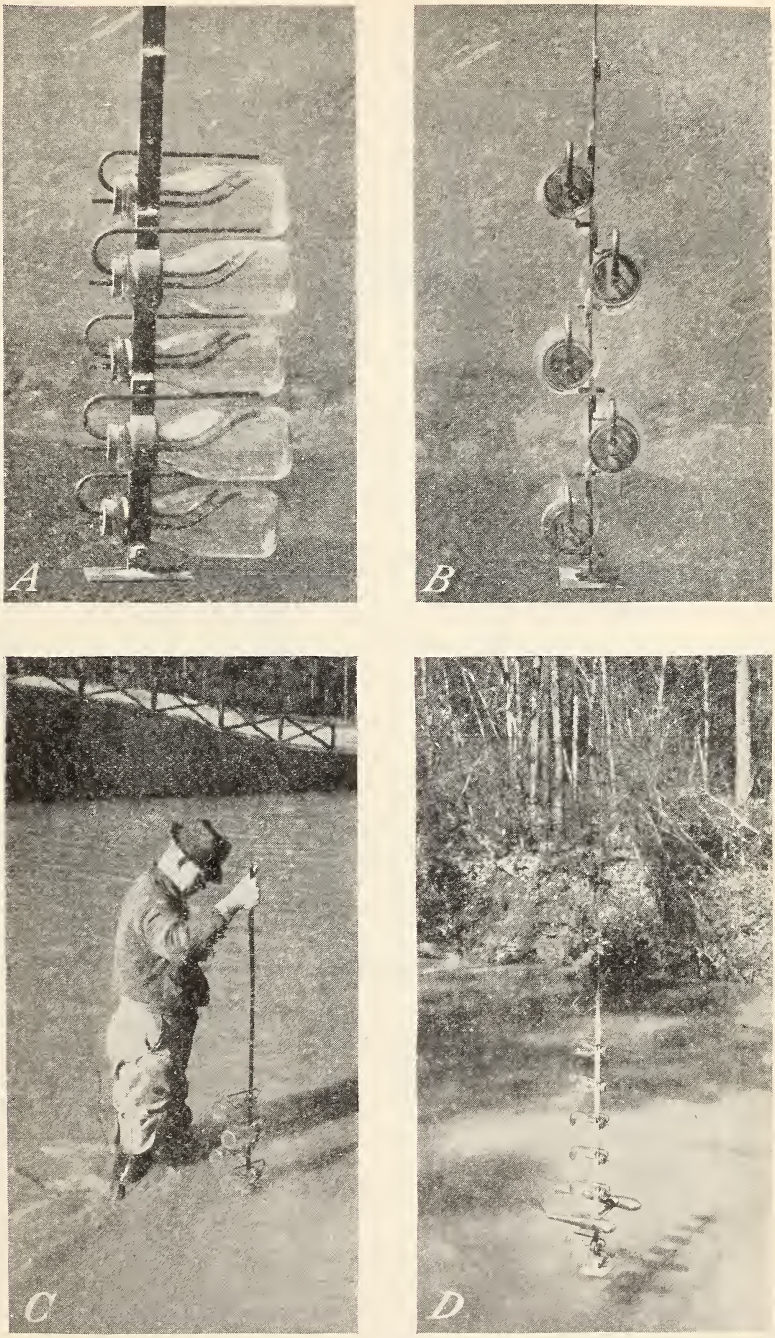

FIGURE 3.—*A*, Side and *B*, front views of multiple arrangement of samplers on wading rod; *C*, observer taking samples by wading, *D*, multiple arrangement of samplers on suspension-type support.

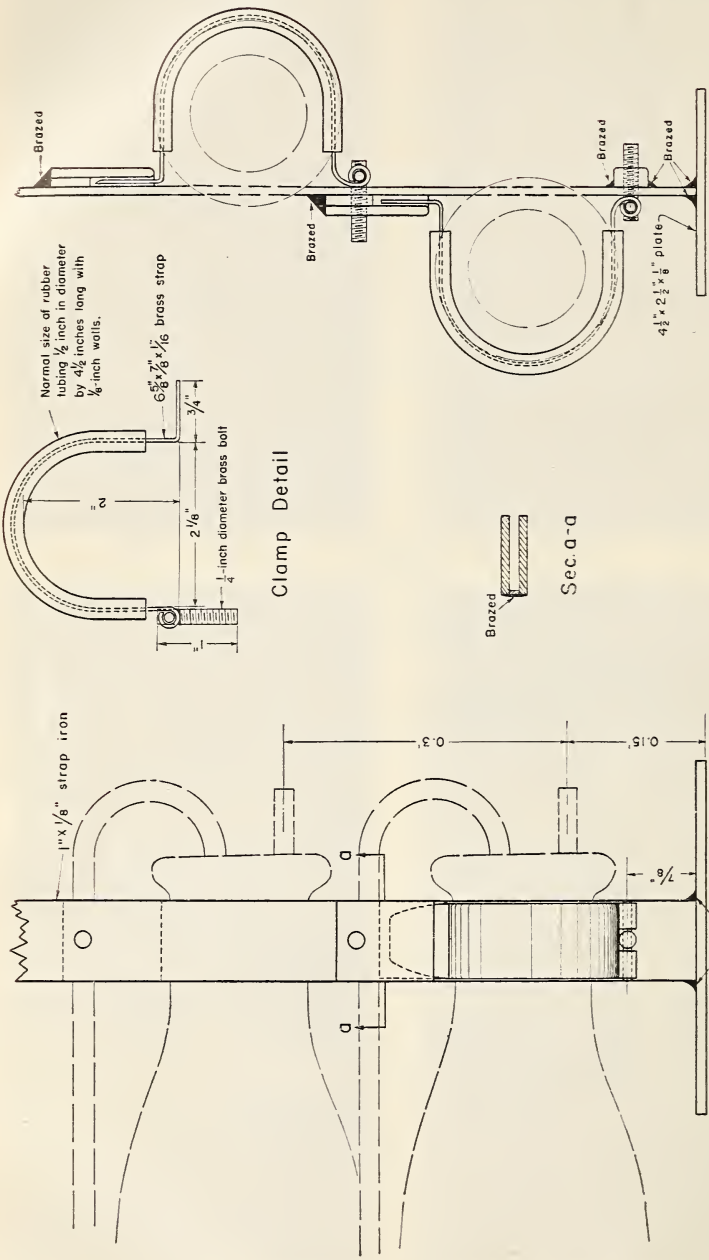

FIGURE 4.—Detail of construction of a support for combination suspended-load sampler and velocity meter.

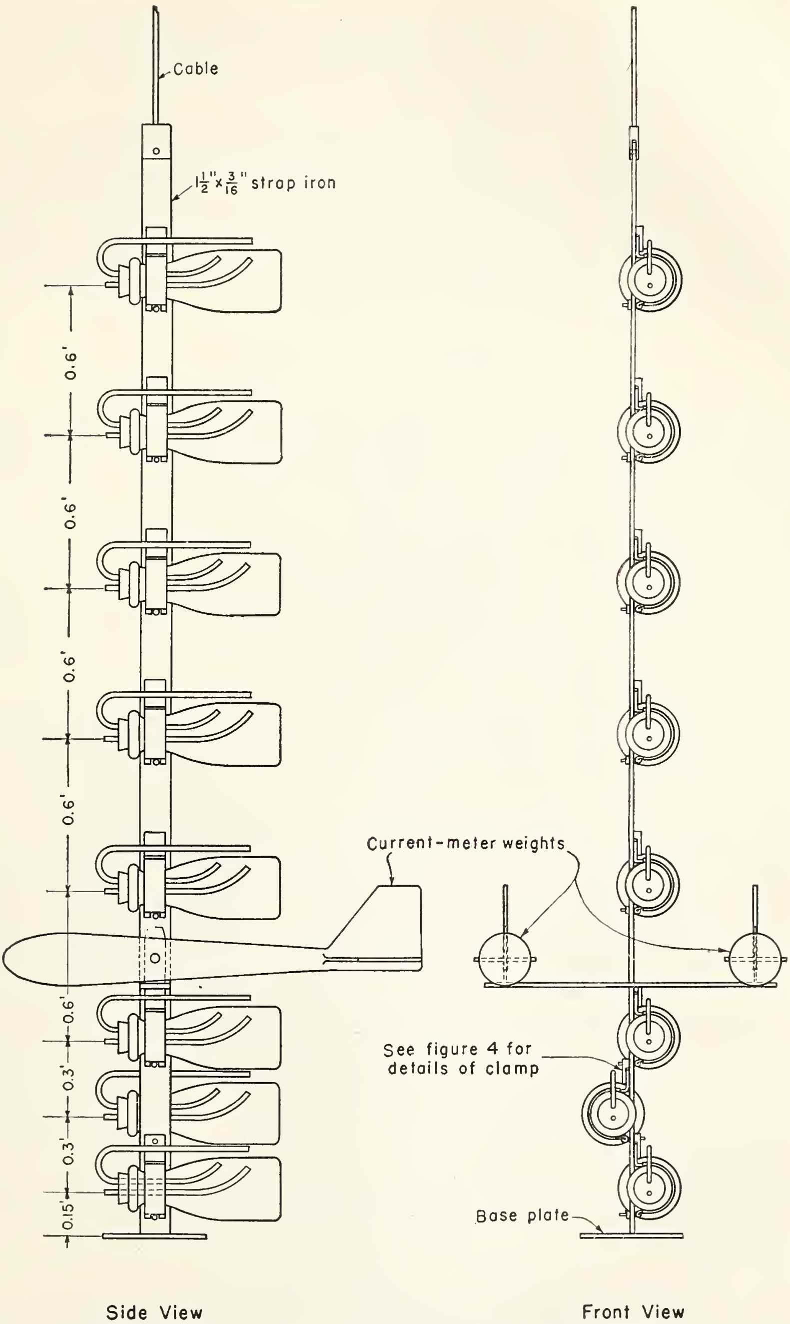

FIGURE 5.—Detail of construction of a cable-suspension support for holding combination suspended-load sampler and velocity meter at 0.3-foot intervals.

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The collection bottles must be securely clamped to the vertical support in such a manner that the samplers can be lowered in horizontal positions facing the current with the upper air-exhaust tube vertical over the lower or water-intake tube.

The purposes for which the data are taken and the cost of determining the sediment content of the samples in the laboratory are prime considerations in deciding the minimum number of samples required in a cross section. These considerations have been sufficiently discussed in other publications (*3*, *5*, *12*). For a particular vertical, decision as to the spacing of a chosen number of samplers throughout the depth, if not formed from experience in previous sampling, may be based on study of the distribution curves shown in figure 1.

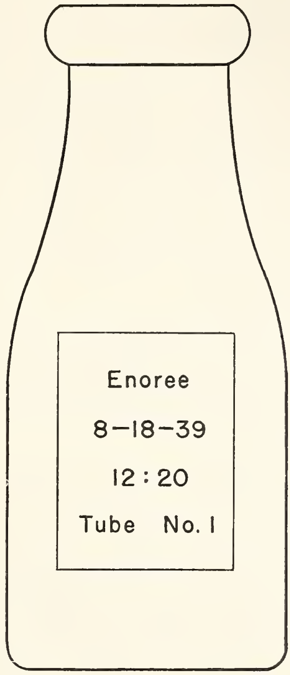
Method of Sampling

If the samples are to be taken while wading, the apparatus is held pointing up current and then quickly plunged into the water and lowered until the base plate rests gently on the bottom. In taking observations from a bridge or cableway, by suspending the apparatus, the position of the water surface first is read from the dial on the reel or on the calibrated cable. The sampler holder is then quickly lowered to the bottom until the base plate rests gently on the stream bed and the depth to the bed read from the reel dial or cable. The position of the various sampling points, with respect to the water surface or the stream bed, is easily determined from the known positions of the samplers on the support.

The operator starts a stop watch the moment the base plate of the holder strikes the water surface. The time interval during which the sampler is submerged depends largely upon the velocity of the stream and the size of the container used to trap the sample. When using a pint milk bottle, the time interval varies from approximately 20 seconds for a velocity of 6 feet per second to 100 seconds for a velocity of 1 foot per second. From a knowledge of the approximate velocity of the stream, the operator can determine the approximate period during which the samplers should remain submerged. Care must be taken that the samplers are not submerged so long as to fill; otherwise the amount trapped bears no relationship to the time of filling and, as a consequence, no velocity determination can be made.

At the conclusion of the period of submergence, the apparatus is quickly withdrawn from the water and the time of submergence determined from the watch. For depths of flow to 6 feet, the sampler can be placed in position and withdrawn in a fraction of a second. The error in filling during this time is negligible. For greater depths, it may be possible to provide a valve arrangement on the tubes to prevent filling of the sampler before a desired point is reached. Such a valve mechanism, however, has not been perfected for this sampler, and its development would doubtless lead to a complex and less wieldy apparatus.

For high-velocity streams, a quart milk bottle may be used to permit a longer period of submergence than could be obtained with a pint bottle. Tubes of different dimensions than those shown in figure 2, however, would be needed. The use of quart bottles has its disadvantages, however, in that the compactness of the apparatus is reduced and the cost of handling the samples in the laboratory is increased.



A

Sample label	Collection time Seconds	Distance above bed Feet	Water depth Feet	Distance from water edge Feet	Width of stream Feet
E8-18-39 12:20-1	20.6	0.15	2.98	14.5	45

B

FIGURE 6.—*A*, bottle labeled, showing field marking, *B*, notebook page, showing field entries.

Immediately upon obtaining a set of samples, the bottles are unclamped from the support, the tubes removed from the bottles, and the bottles securely capped. Each bottle is properly marked with the date and hour of collection, the name of the stream, and other pertinent data. A typical marking is shown in figure 6 (*A*).

The bottles are then sent to the research laboratory. To assist in identifying and analyzing the various samples in the laboratory, it has been found desirable also to make a record in the field in a notebook of the name of the river, date and hour of sampling, the sampler-tube number, period of submergence, distance of sampler above river bed, river stage, position of vertical with respect to reference point on bank, and surface width of the stream. A typical set of field notes corresponding to the marking on the bottle in figure 6 (*A*) is shown in figure 6 (*B*).

In some streams at certain times of the year difficulty may be experienced with leaves or other debris obstructing flow into the entrance tube. In a multiple arrangement of samplers a stoppage of one of the samplers is easily noted by observing an unusually low amount of water in certain bottles.

Velocity Calibration

The adaptability of the apparatus to use as a velocity meter is based upon the principle of collecting a measurable volume of water through a tube of definite size over a definite period of time. Bernoulli's theorem (*11*) states that in steady flow with friction, the total head, which is the sum of the velocity head, pressure head, and potential head, at any section is equal to that at any subsequent section plus the loss of head occurring between the two sections. By applying this theorem it is apparent from figure 2 that where

v_s = velocity of the stream,
v_t = velocity in the water tube,
h' = total loss of head through the tube,
b = constant static head on the tube (fig. 2), and
g = acceleration of gravity

$$\frac{v_s^2}{2g}=\frac{v_t^2}{2g} \tag{1}$$

By assuming a loss in the outside flow between the entrance to the sampler and the air outlet, a coefficient is obtained for the right side of equation 1. The head loss, h', is a function of the velocity in the tube. When the stream velocity is large, the static head b is negligible and the velocity in the stream is then directly proportional to the velocity in the tube. The rate at which the bottle is filled is a function of the velocity of water passing into it; therefore, the velocity of the stream at the point of sampling can be determined from the time of submergence and the volume of the sample collected. The relationship between the stream velocity and the rate of collection is obtained by calibrating the tubes of each sampler.

Figure 7 shows the calibration curve for one sampler. It was obtained by attaching the sampler to a carriage and moving it at constant speeds through still water. The time required to traverse a fixed distance and the rate of collection of water in the sampler

were noted. The equivalent velocity of the stream in feet per second was then plotted against the rate of collection in cubic centimeters per second. The fact that the greater portion of the calibration curve is a straight line indicates that the velocity in the tube can be considered directly proportional to the velocity of the stream. For this sampler the tube velocity was found to be approximately seven-tenths of the stream velocity.

When the stream velocity decreases to about 1.2 feet per second the effect of the constant static head b becomes appreciable and of the same magnitude as the velocity head, thus increasing the velocity in the tube.

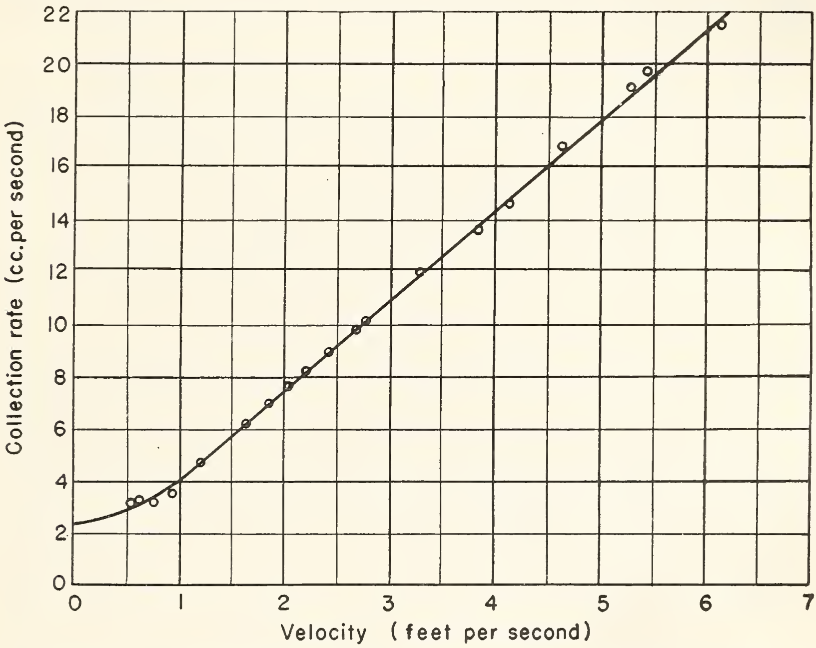


FIGURE 7.—Velocity calibration curve for sampler No. 1, corrected for depth.

DEPTH CORRECTION

A correction for depth of submergence must be made because of the compression of the air in the container, which is at atmospheric pressure immediately before submergence, but is compressed by the water in proportion to the depth of the sampler as it is lowered into the stream. Therefore, at any given depth the additional volume of water which enters the container due to compression of the air must be subtracted from the total volume collected before the velocity curve can be applied.

The change in volume can be computed from Boyles law,

$$P_1V_1=P_2V_2 \text{ or}$$

$$V_2=V_1\frac{P_1}{P_2}$$

where P_1 and V_1 are original absolute pressure and volume of container and P_2 and V_2 are final pressure and volume of the compressed air. Since P_1 is 14.7 pounds per square inch and P_2 is the pressure P_1 plus the additional water pressure in pounds per square inch at the depth of water, that is

$$P_2 = 14.7 + d \times \frac{(62.4)}{144}, \text{ then}$$

$$V_2 = \frac{14.7 V_1}{14.7 + d \frac{(62.4)}{144}} \tag{2}$$

where d is depth in feet of submergence of the center of the exit end of the water tube.

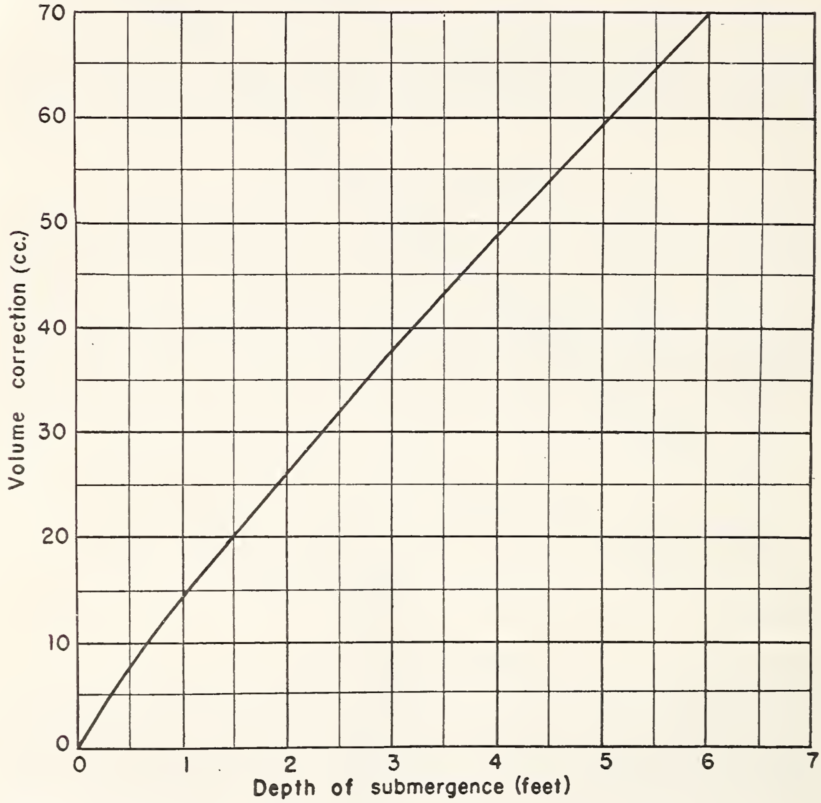


FIGURE 8.—Volume correction for various depths of submergence for pint milk bottles, proper allowance having been made for volume occupied by stopper and tubes.

The correction must be subtracted from the measured volume trapped before the rate of collection can be computed. Figure 8 shows the correction to be applied for various depths when a pint milk bottle is used as the container, proper allowance being made for space occupied by stopper and tubes. The corrections are applied in the

laboratory, where also the discharge of the stream is computed from the volume of the sample and field notes, and hence these calculations are no burden on the sample collector.

Sample Computation

From the field observations and the laboratory analysis of the sample described in figure 6 the following data were obtained:

Sample No. E8–18–39—12:20–1:

Sampler No. 1:

Distance from right bank water edge	feet	14.5
Distance from water surface	do	2.83
Depth of water	do	2.98
Collection time	seconds	20.6
Volume collected	cubic centimeters	335.0
Weight of mixture [3]	grams	335.0
Weight of sediment, dry	do	0.2787

Concentration.—The concentration C is determined in parts per million; the formula is:

$$\text{Concentration in parts per million}=\frac{\text{dry weight of sediment}}{\text{weight of mixture}}\times 1{,}000{,}000.$$

Using this formula, the calculation from the data for sample No. E8–18–39—12:20–1 is:

$$C=\frac{0.2787}{335.0}\times 1{,}000{,}000=832 \text{ p. p. m.}$$

Velocity.—The velocity of the stream (v_s) is determined in feet per second.

Referring to figure 8, a volume correction of 35.6 cubic centimeters is obtained for depth of submergence of 2.83 feet. Subtracting 35.6 cubic centimeters from the collected volume of 335.0 cubic centimeters, the corrected volume is calculated to be 299.4 cubic centimeters.

Dividing the corrected volume by the collection time gives the rate of collection.

The calculation is:

$$\frac{299.4}{20.6}=14.53 \text{ cc. per second.}$$

Referring to figure 7, it is determined that a rate of 14.53 cubic centimeters per second corresponds to a stream velocity of 4.05 feet per second;

$$v_s=4.05 \text{ feet per second}$$

HYDRAULICS OF THE COMBINATION SUSPENDED-LOAD SAMPLER AND VELOCITY METER

The value of any sampler depends primarily upon its accuracy in obtaining a representative sample of the suspended load at the point being sampled. In the use of a tube sampler, a number of conditions exist that may have an important effect upon its efficiency to trap such a sample.

[3] In studies where small percentages of load exist, the density of the mixture is assumed to be 1.0, and hence the volume in cubic centimeters is equal to the weight in grams.

A simple analysis of the conditions that exist near the opening of the tube may show some of the factors involved. For this analysis, the assumptions are made (1) that the flow near the opening is substantially steady and uniform, (2) that the concentration of suspended load is also substantially uniform near the entrance and is constant during the time the sample is being collected, (3) that the particles move with the velocity of the water, and (4) that the particles have a uniform specific gravity.

Due to the energy loss in the water tube of the sampler, the velocity through the tube normally is less than the velocity of the stream being sampled. Because of this reduced velocity in the tube, the area of the filament of water in the stream is less than the area of the tube. A short distance from the entrance, the streamlines of this filament curve outward until the filament, upon entering the water tube, has the same diameter as the tube. This phenomenon is shown schematically in figure 9.

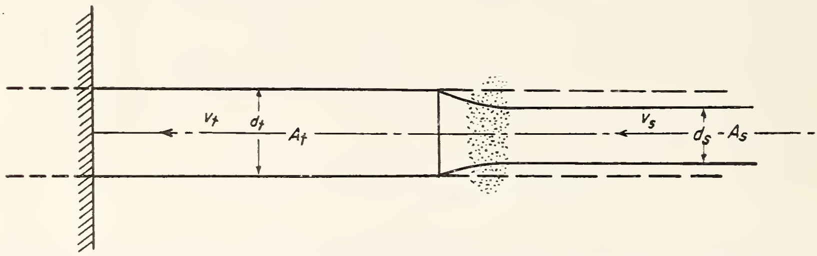


FIGURE 9.—Schematic representation of suspended-load sampler water tube and filament of water in stream, approaching tube.

The inertia of the particles in the curving streamlines outside the filament, that is in the annular area between the filament and the tube projected, tends to throw them out of these streamlines and into the tube opening. If the ratio of the velocities is equal to unity, the area of the filament will equal the area of the tube; only the particles in the filament will enter the tube; and the concentration measured will therefore be equal to the concentration of the stream. As the ratio of the stream velocity to the tube velocity increases, the area of the filament in comparison with that of the tube will be decreased and the annular area increased so that a greater proportion of the particles in suspension near the entrance will be thrown into the tube opening.

At the same time, the inertial force of the particles increases with their mass, so that, for a given ratio of the two velocities, the apparent concentration of the stream, as indicated by the sampler, will increase with some function of the mass.

In expressing these relationships the following notation will be used:

A_s=area of filament of water a short distance upstream from the tube.
v_s=velocity of the filament and the stream a short distance upstream from the tube.
A_t=area of sampling tube.
v_t=velocity of water in the tube.
N=number of particles in suspension per unit volume of water in the stream.
C_s=concentration of suspended material trapped in the sampler.
C_t=concentration of suspended matter in the stream.
p =proportion of particles in the annular area between the filament and the tube projected that will enter the sampling tube.

d_p=diameter of the particle.
d_t=diameter of the tube.

It can be shown by referring to figure 9 that the concentration of particles collected in the trap in a short time, Δt, is equal to the concentration of particles in the water filament that enters the tube plus the probable proportion of the concentration between the areas, A_s and A_t, that will be thrown into the tube because of the inertia of the particles, or

$$C_t = NA_s v_s \Delta t + pN(A_t - A_s) v_s \Delta t \tag{3}$$

The actual concentration of suspended matter in the stream to be measured by the sampler is simply

$$C_s = NA_s v_s \Delta t \tag{4}$$

The ratio $\frac{C_t}{C_s}$ then becomes

$$\frac{C_t}{C_s} = \frac{NA_s v_s \Delta t + pN(A_t - A_s) v_s \Delta t}{NA_s v_s \Delta t} = 1 + p\left(\frac{A_t}{A_s} - 1\right) \tag{5}$$

From the continuity of flow

$$\frac{A_t}{A_s} = \frac{v_s}{v_t} \text{ or } A_s v_s = A_t v_t \tag{6}$$

Substitution of equation 6 in equation 5 gives the ratio of concentration as

$$\frac{C_t}{C_s} = 1 + p\left(\frac{v_s}{v_t} - 1\right) \tag{7}$$

In equation 7, p, which is the proportion of the particles in the annular area between the filament and the tube projected that will enter the sampling tube, may vary from zero to unity. When $p=0$, no extraneous particles will enter and the concentration measured will be equal to the actual concentration of the stream. When $p=1$, all of the grains in this area will enter the tube. Equation 7 indicates that p is also the slope of a straight line passing through the point $C_t/C_s=1$ and $v_s/v_t=1$ in rectangular coordinates. Considering the actual concentration of the stream to be measured by the suspended-load sampler as an unknown function given by

$$C_s = f(C_t, v_s, v_t, d_p, d_t) \tag{8}$$

dimensional analysis indicates that the form of the equation describing the action may be

$$\frac{C_t}{C_s} = f\left(\frac{v_s}{v_t}, \frac{d_p}{d_t}\right) \tag{9}$$

By a comparison of equations 7 and 9, p is probably dependent upon some function of the radio d_p/d_t, since the ratio v_s/v_t already appears in the equation. This is in accordance with the previous reasoning that for particles of greater mass, the inertial forces become greater and the value of p should also increase. Inasmuch as the sampler is used to trap particles of a considerable range in size and since in addition the velocity in the tube is normally less than the stream velocity, it could be expected that the concentration as measured by the sampler would in general be somewhat greater than the actual concentration of the stream.

A series of tests were designed to determine whether the curvature of the streamlines as implied by a value of v_s/v_t greater than unity or a variation in the average size of the particles causes a change in the apparent concentration of particles in the stream, as indicated by the sampler, and to determine the approximate magnitude of such change.

Experimental Equipment

By making experiments in a small circulating flume, using sediment of several sizes, and controlling the ratio of the stream velocity to the tube velocity, the variation due to change in v_s/v_t and d_p/d_t was determined. With the velocity of the stream held substantially constant, the tube velocity, v_t, was controlled by regulating the flow of air from the sampler. This was done with a simple suction device, consisting of an inverted water-filled flask to which the air tube of the sampler was connected by rubber tubing. The rate at which the air was withdrawn from the sampler and, hence, the rate at which water entered through the tube was governed by the rate of flow from the flask. By this means, v_t could be varied approximately from eight-tenths to eight times the velocity in the stream.

The sediment used in the experiment consisted of standard sieve separates in the following grades:

Size range (millimeters):	*Sieve No.*
<0.074	Passing 200.
0.074 to 0.088	200 to 170.
0.088 to 0.124	170 to 115.
0.124 to 0.175	115 to 80.
0.175 to 0.246	80 to 60.

The circulating flume (fig. 10), consisted of a channel lined with galvanized sheet metal, 6 inches wide, 10 inches deep, and 8 feet long, through which water was circulated by a portable pump (9,000 gallons per hour capacity) at a velocity between 2½ and 3 feet per second. The total volume of the system in circulation was approximately 50 gallons.

Experimental Procedure

Several series of experiments were carried out for each grade size using different stream concentrations. An amount of sediment was added to the system such that for each series a different concentration was obtained. These concentrations ranged from 200 to 1,800 p. p. m.

Since the concentration of the suspended load in a circulating flume is not uniformly distributed, the average concentration in the system is not necessarily equal to the concentration at any particular point. It was assumed, however, that if all the hydraulic conditions were held constant, the concentration at a particular point would remain substantially constant. For this reason, after the sediment had been introduced and the flow conditions had become steady, all of the samples for a given series were collected at one point in the cross section.

During the course of collecting the samples of a single series, every third measurement was made without artificial suction, both

to determine the average velocity of the stream for the series and as a control for the experiment. The velocity of the stream was obtained from the velocity calibration curve of the sampler used.

One series of experiments was carried out with a sampling tube of a smaller diameter ($d_t = 0.32$ cm.) to test the validity of the statement that p is dependent upon some function of the ratio of the diameter of the particle to the diameter of the sampling tube.

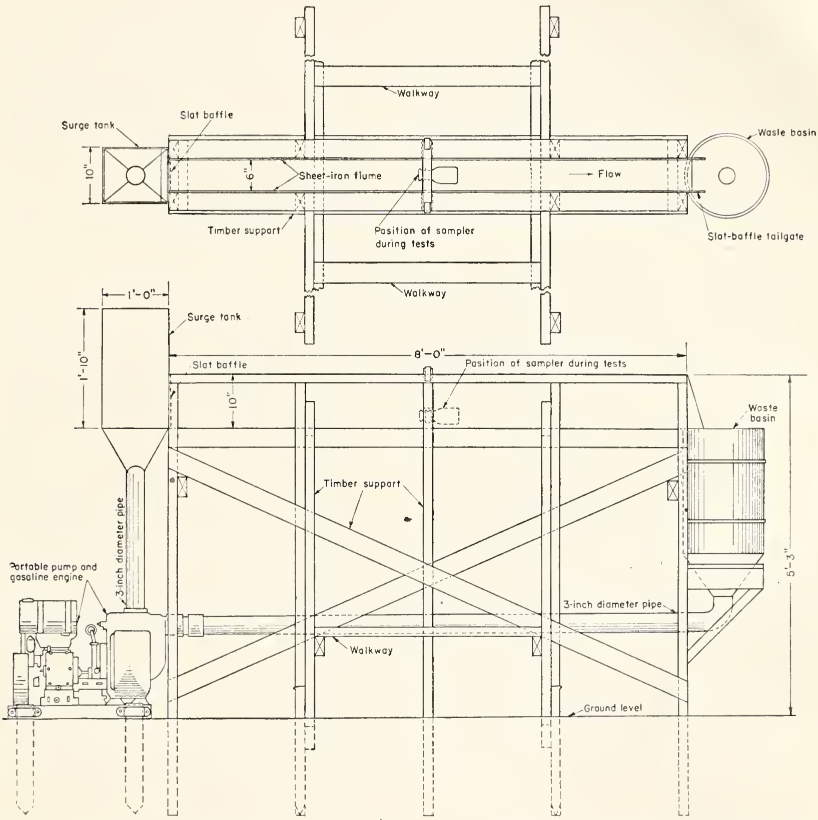


FIGURE 10.—Drawing showing construction of a small circulating flume used in hydraulic experiments to determine the variation in particle concentration resulting from changes in the ratios of stream velocity to tube velocity and particle diameter to tube diameter.

The concentration of suspended material was determined by the usual laboratory methods. In this case, the sand particles for all except the finest grade were separated from any extraneous finer material by decanting, after having been dispersed and allowed to settle for a period long enough to allow the deposition of particles of the size used in the test. After decanting, the residue was filtered through filter crucibles, and the deposit was dried and weighed. For the finest grade, the decanting process was eliminated.

Experimental Results

The results of the several series of tests for each grade size are plotted in figure 11, where the ratios of the velocity of the stream to the velocity in the tube, v_s/v_t, are plotted as abscissas and the

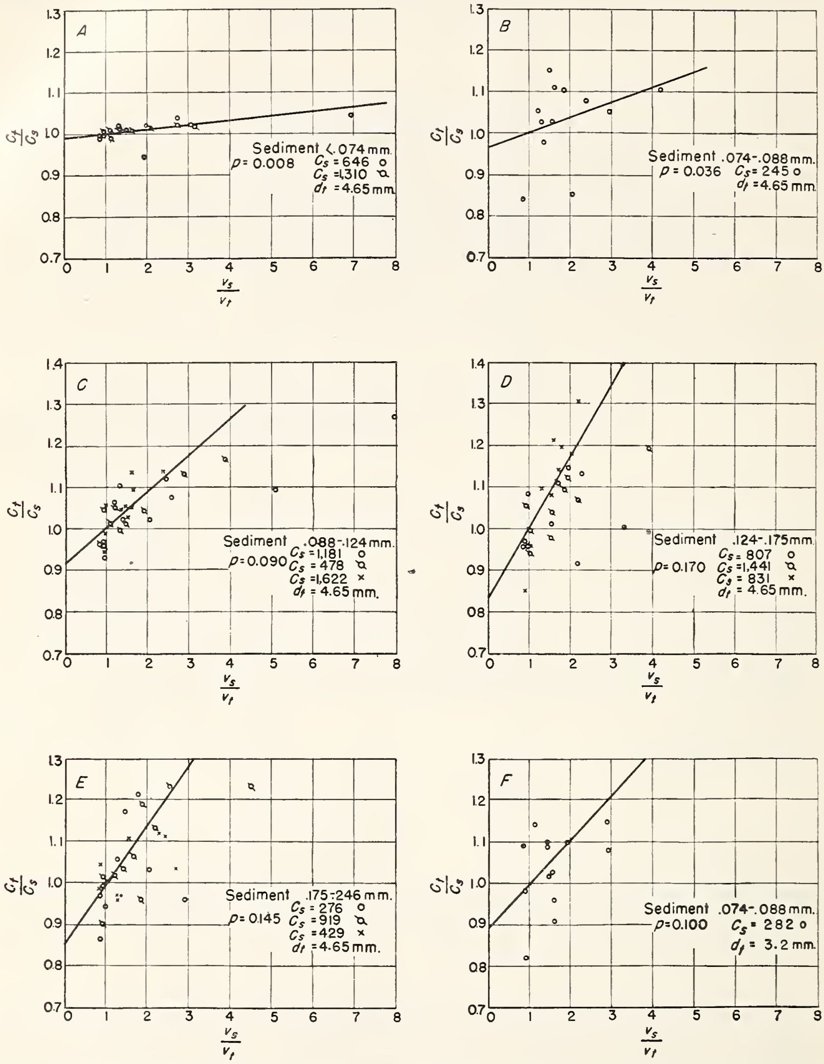


Figure 11.—Results of hydraulic experimentation to determine the effect on concentration of particles of varying sizes attributable to changes in ratio of stream velocity to tube velocity.

ratios of the concentration trapped in the sampler to the actual concentration of the stream, C_t/C_s, as ordinates. The actual concentration of the stream, C_s, is defined as the concentration trapped when v_s/v_t is equal to unity (equation 7). This value was obtained from

a preliminary plot of observed values of the measured concentration C_t for each series against observed values of v_s/v_t. By this manner of plotting, the several series for each grade were placed upon a common base for comparison, as shown in figure 11. The most probable line was fitted by the eye to the group for each grade size.

Although there is a considerable scattering of points, the trends of the data for the various grades are quite apparent. Most of the scatter probably can be ascribed to variations in concentration inherent in the use of the circulating flume, due to variations in water velocity and turbulence. Some scatter is also due to the fact that the sediment in each grade was not closely graded, but covered a wide range compared to the total range of sizes used. Other causes of scatter may be errors in collecting and analyzing the samples.

The curves for each grade indicate that the inertia of the particles in the curved streamlines outside the filament is sufficient to force some of them into the sampling tube when the tube velocity becomes less than the stream velocity, that is, $v_s/v_t>1$, and that the proportion becomes greater as the tube velocity becomes smaller in comparison to the stream velocity. Comparison of the curves of the several grade sizes also indicates that the increase in concentration for a given velocity ratio, v_s/v_t, becomes greater as the average diameter of the grade increases.

Significance of Experiments

The curves shown in figure 11 can be described by an equation which is identical with equation 7, founded on fundamental hydraulic theory, where p, the slope of the curve for each grade, is the proportion of particles in the annular area outside the filament that enters the tube. As is apparent from the curves and as indicated by dimensional analysis, p is probably some function of the diameter of the particle. In figure 12, is plotted the value of p, as defined by the slope, against the ratio of the diameter of the particle to the diameter of the sampling tube, d_p/d_t.

When plotted on logarithmic paper the points produce a straight line, whose equation is of the form:

$$\text{Log } p=\log k+n \log \left(\frac{d_p}{d_t}\right) \tag{10}$$

Correspondingly, the data, when plotted on arithmetic cross-section paper produce a parabola, the equation of which is

$$p=k\left(\frac{d_p}{d_t}\right)^n$$

From the logarithmic plot, the exponent n is found to be equal to 2, indicating that p is proportional to the ratio of the projected area of the particles to the area of the sampling tube. The fact that the result of the tests using a sampling tube with an inside diameter of only 3.2 mm. also falls on this curve substantiates the assumption that the diameter of the tube as well as the diameter of the particle controls the magnitude of p.

As a result of these experiments, means are available by which the concentration of the stream as measured by this type of sampler

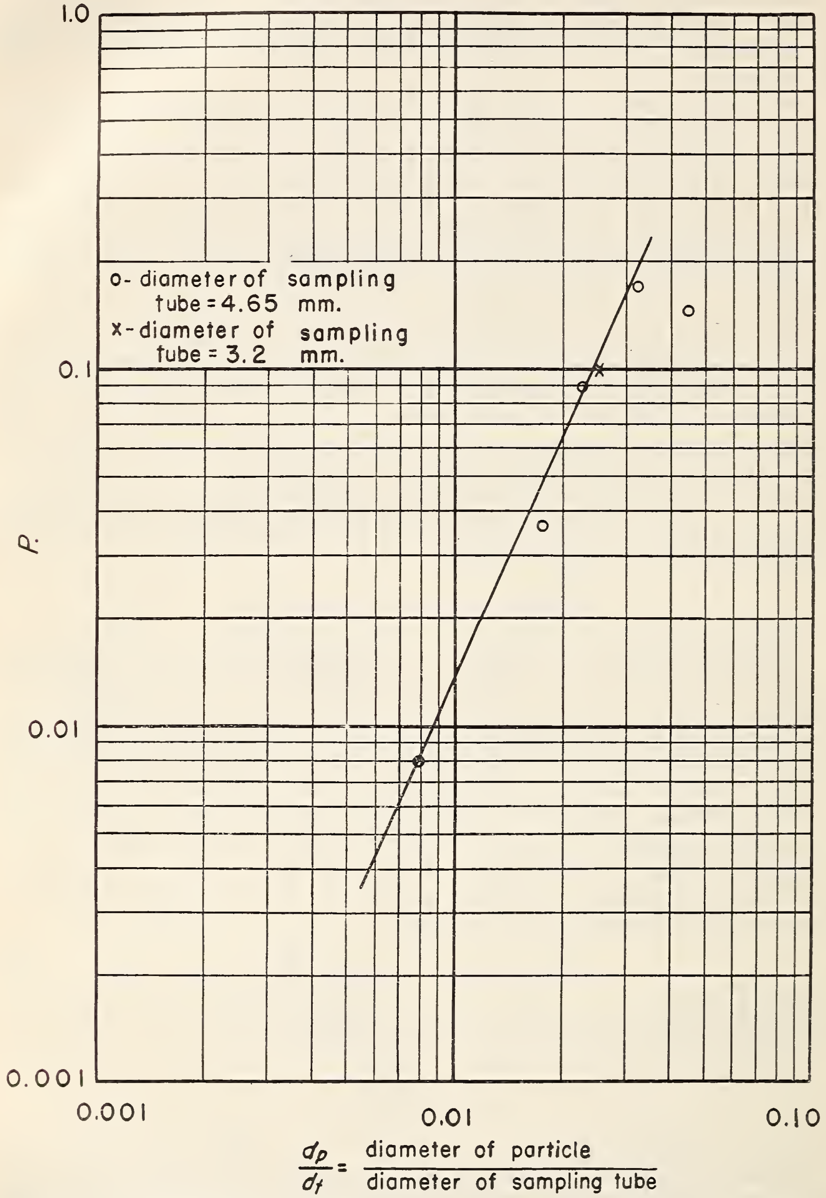


FIGURE 12.—Relationship of p to the ratio of diameter of particle to diameter of sampling tube.

may be corrected to take into account the effect of the curvature of the streamlines resulting from the difference in velocity of the

stream and the velocity in the tube. This correction is made by using figure 13, which shows a curve for the ratio of C_t/C_s for various particle sizes. This curve applies only to the quarter-inch diameter sampler tubes in which the velocity ratio, v_s/v_t, is 1.4, as found by experiment. The concentration of a particular particle size in the stream is equal to the concentration trapped in the sampler divided by the ratio shown in figure 13.

For ordinary purposes this correction, in comparison with other sampling errors and the accuracy of analysis, may be negligible, and need be applied only when exceptional accuracy is required in special studies. As an illustration, the magnitude of the correction for particles 0.01 mm. in diameter is only about 0.1 percent, while for particles

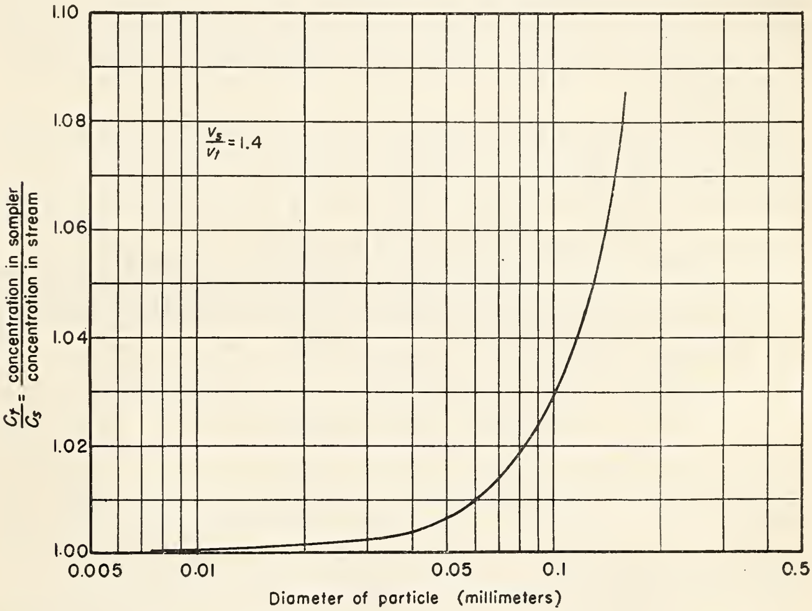


FIGURE 13.—Concentration correction curve for a one-fourth-inch sampling tube for curvature of streamlines resulting from changes in ratio between stream and tube velocity for particles of varying diameters..

approximately 0.10 mm. in diameter the correction is approximately 3 percent. Although the error increases rapidly with the size of the particles, the number of particles in suspension normally decreases rapidly as the diameter becomes greater, so that the absolute correction may be quite negligible in comparison with the total suspended load.

For the majority of the smaller streams in which this type of sampler is expected to find its greatest application, the larger proportion of the suspended load is, as a rule, less than 0.01 mm. in diameter. For instance, Faris (*3*) reported that in Texas streams more than 97 percent of the suspended load, on an average, passed a standard type No. 300 sieve (0.046 mm.). Love (*10*) found very little material coarser than 0.05 mm. on streams in North Carolina, Texas, and Oklahoma. Fortier and Blaney (*5*) reached similar conclusions.

Figure 1 shows the relative quantities of various sizes obtained by a multiple arrangement of samples (fig. 3). In figure 1, the concentrations and the velocity are shown for several points in the vertical. The sediment greater than 0.01 mm. in each sample was analyzed for mechanical composition by means of a microscopic count of the various particles. The cumulative concentration of the various particle sizes is plotted horizontally for each point in the vertical. The area under the curve marked 0.03 mm. represents the concentration of suspended matter consisting of particles smaller than 0.03 mm. in diameter. The area between the base line and the next curve represents the concentration of particles finer than 0.075 mm. in diameter, and so on. Thus the area between the seventh and eighth curves represents the concentration of particles between 0.50 and 0.70 mm. Here again the greater percent of the total load consists of material finer than 0.03 mm. in diameter. The curves are regular, showing increasing concentration near the bottom of the stream for the various particle sizes.

Superimposed upon the velocity curve as measured by the sampler are the results obtained by measuring the velocity with a Price current meter. The agreement of velocity between the sampler and the current meter shows a maximum difference of approximately 6 percent, but, in general, the agreement is much closer.

In the analysis of the hydraulics of the tube, certain assumptions were made in order to simplify the resulting equations. The effect of the turbulence of the stream and the momentum exchange affecting the particles in suspension were disregarded.

As the ratio of the stream velocity to the tube velocity, v_s/v_t, becomes greater, the area of the filament of water entering the tube becomes smaller in comparison with the area of the tube. Increasing v_s/v_t, for a given particle size, increases the concentration near the entrance of the tube, making it greater than in the area outside of the tube. Hence, any exchange of sediment that takes place will decrease the concentration near the entrance and, hence, decrease the value of p. It seems therefore that p is a function of v_s/v_t, as well as d_p/d_t, and that for a given particle size p decreases with increasing velocity ratio. However, for the samplers tested, the velocity ratio ranges approximately 1.4 and the corresponding ratio of areas is therefore approximately 0.7, so that the effect of turbulence in lowering the magnitude of p is so small that it can be determined only in experiments of greater precision.

CONCLUSIONS

The combination suspended-load sampler and velocity meter described in this publication is useful especially for sampling small streams, a program of sampling in which the United States Department of Agriculture is greatly concerned. It is most accurate when the submergence depth is less than 6 feet, the velocity is less than 6 feet per second, and the suspended load has only a small fraction of particles greater than 0.10 mm. in diameter.

Other sizes of tubes and larger bottles may be used to meet certain field conditions, but in the majority of suspended-load sampling, a satisfactory instrument will consist of a properly calibrated pint milk

bottle with tubes constructed of copper or stainless steel, one-quarter of an inch in diameter.

This type of sampler has many advantages in addition to the usual features possessed by other samplers designed for use in small streams. Among them are that a time-integrated sample of suspended-load sediment and water is collected within a relatively small area (sampling point) in the stream cross section, that the stream velocity can be measured at the same time and at the same point that sediment concentration is measured, that the cost of constructing and calibrating the sampler is small, that a number of samplers on a single support permits a determination of the vertical distribution of suspended matter, that errors induced by transferring the sample of water and sediment to another container for transmittal to the laboratory are eliminated, and that sampling is easy and rapid.

The sampler is particularly well suited for work on small streams where a discharge rating curve is not available, for, by using the instrument as a velocity meter, such a rating curve can be constructed. The agreement of the velocity as measured by the sampler with that measured by a Price current meter has shown a maximum difference of approximately 6 percent, but in general the agreement is much closer.

Experiments show that particles in the curving streamlines between the water filament entering the tube and the tube projected are diverted into the entrance tube when the tube velocity is less than the stream velocity, but the error involved is probably less than the other inherent errors of sampling. For ordinary sampling this error may be disregarded.

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